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Review article from invited author

Endodontic hand instruments: cutting efficiency, instrumentation of curved canals, bending and torsional properties

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Abstract – In an assessment of the usefulness of different root canal instruments, two aspects are of particular interest for the endodontist: the cutting efficiency of the instruments and their ability to enlarge curved canals without undesirable changes of the canal shape such as the formation of zips and elbows. This review paper is based on own investigations on the cutting efficiency and instrumentation of curved canals. Additionally, two parameters which are described in ISO 3630-1, resistance to bending and resistance to fracture, are discussed. With regard to cutting efficiency in rotary motion, flexible stainless steel reamers and K-files clearly display the best results and are superior to conventional stainless steel as well as titanium-based reamers and K-files. Regarding cutting efficiency in linear motion, stainless steel Hedström files made by certain manufacturers are significantly superior to stainless steel and titanium-based Hedström files of other brands. Flexible stainless steel instruments with modified noncutting tips clearly produce the best canal shape in curved canals. With only rare exceptions, all the instruments tested fulfilled the requirements of the ISO standard concerning resistance to fracture and resistance to bending.

Key words: curved root canals; endodontic instruments; endodontic treatment; root canal instrumentation

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Root canal instruments for manual use have been modified during the last years with regard to the use of both new alloys and new design features (1).

Stainless steel root canal instruments for manual use can be divided into conventional stainless steel and the so-called flexible stainless steel instruments. The new alloys have to a certain extent been used in other fields of dentistry. This is the case with nickel-titanium, which has been used in orthodontics in nickel-titanium wires (2). Moreover, instruments made of a titanium-aluminium alloy have been available since 1994. An overview of the variety of root canal instruments for manual use with respect to their shape, alloys and certain clinical properties has been given in a previous article (1).

This paper presents a discussion, based on own investigations, of the cutting efficiency of various hand instruments, the instrumentation of curved canals with different instruments and instrumentation techniques, and the bending and torsional properties of the instruments. The instruments tested are listed in Table 1.

Table 1. The instruments discussed in this paper

Group	Manufacturer	Instrument
Conventional stainless steel instruments	Kerr Karlsruhe, Germany Komet (Gebr. Brasseler) Lemgo, Germany Maillefer Ballaigues, Switzerland Mani Nakaakutsu, Japan Meisinger Düsseldorf, Germany Micro-Méga Besançon, France VDW Munich, Germany	From each manufacturer: reamer K-file Hedström file
Flexible stainless steel instruments	Kerr Karlsruhe, Germany Maillefer Ballaigues, Switzerland Union Broach New York City, NY, USA VDW Munich, Germany	K-Flex K-Flexofile[1] K-Flexoreamer[1] Flex-R file[2] Flexicut
Titanium-aluminium	Micro-Méga Besançon, France	reamer K-file Hedström file
Nickel-titanium	Mity Ridgefield, CT, USA	Hedström file K-file

[1] Available with noncutting tip in ISO sizes 15 to 40.
[2] Available with noncutting tip in ISO sizes 10 to 140.

Design of root canal instruments and their working motion

In principle, root canal instruments for manual use comprise three different types according to their design: reamers, K-files and Hedström files. According to ISO standardization (3), reamers are symbolized by a triangle, K-files by a square, and Hedström files by a circle. However, these symbols do not necessarily represent the true cross-section of the instruments. Most reamers, for instance, are made from square blanks, at least up to size 25.

A fundamental difference between the three different instrument types is the angle of their cutting edges to the long axis of the instruments. This angle determines the most effective working motion of the instruments (Fig. 1). For reamers and K-files the angle between the cutting edge and the long axis is less than 45°. Thus, these instruments are primarily designed to be used with a rotary motion. On the other hand, Hedström files show an angle of the cutting edges to the long axis of about 60° to 65°, and therefore these instruments are primarily designed to be used with a linear, filing motion.

Cutting efficiency

The investigation of the cutting efficiency in a rotary as well as in a linear motion was conducted under standardized conditions, using two specially designed testing devices.

Rotary working motion

Cutting efficiency in a rotary motion was determined using specimens with a cylindrical canal. The specimens were made of a polyester resin (Alpolit UP 004, Hoechst, Hamburg, Germany) to which 5% wt quartz powder was added (4, 5). The abrasion characteristics and the microhardness of this resin were similar to the dentin of the human root canal wall and offered uniform and reproducible abrasive characteristics (6). A specially designed computer-driven testing device which simulated manual instrumentation analogous to the reaming working motion was used (Fig. 2). Furthermore, different instrumentation techniques could be simulated with this testing device so that the ability of different techniques to maintain the original canal shape and curvature during enlargement could

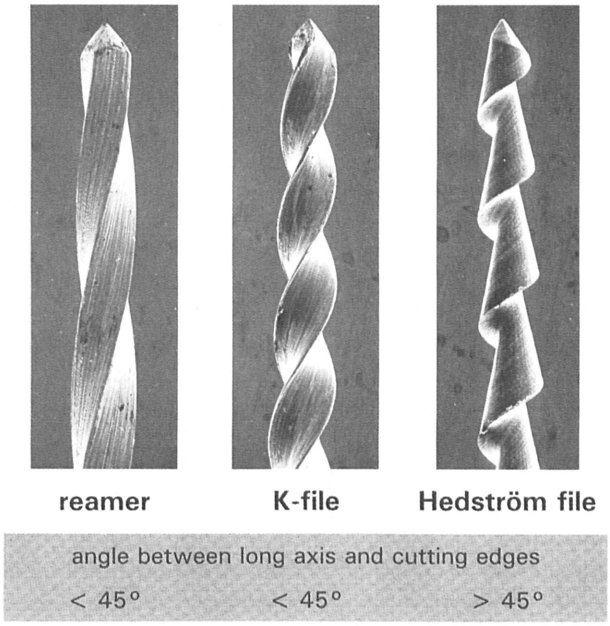

Fig. 1. SEM photograph of different root canal instruments (ISO size 35, original magnification ×40). A fundamental difference between reamers, K-files and Hedström files concerns the angle of the cutting edges to the long axis of the root canal instrument. For reamers and K-files this angle is less than 45°, for Hedström files it is more than 45°. Therefore reamers and K-files are primarily designed for a rotary, reaming motion whereas Hedström files are primarily designed for a linear, filing motion.

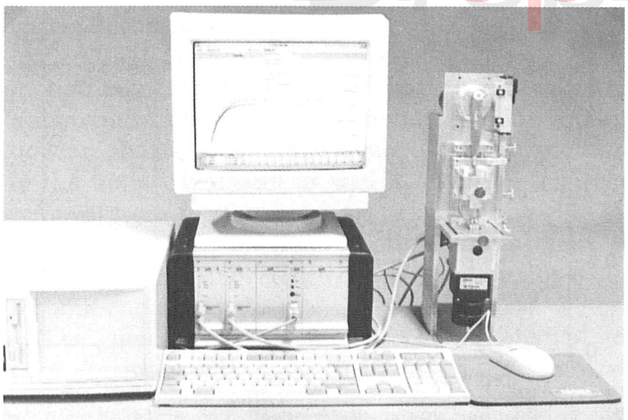

Fig. 2. Computer-driven testing device for standardized investigations on the cutting efficiency of root canal instruments and on the changes occuring in the shape of curved canals due to instrumentation. The testing device generates a rotary working motion, which is controlled by the specially designed software and can be modified in order to simulate different instrumentation techniques. On the computer screen, some original cutting efficiency curves are displayed.

be compared. The construction and the function of the testing device has been described in detail in previous papers (4, 5, 7, 8).

To determine cutting efficiency, each experiment was carried out until the test instrument was verifiably blunt and did not remove any more material. At this time, the maximum penetration depth of the instrument into the cylindrical lumen was reached. The maximum penetration depth served as the criterion for cutting efficiency and therefore was used as the basis for comparison (4).

The investigations on cutting efficiency were performed with conventional stainless instruments, flexible stainless steel instruments with conventional or modified tips, instruments made of titanium-aluminium and nickel-titanium alloys (Table 1). Instrument sizes 25 and 35 were tested.

The results were similar for size 25 and size 35 instruments and can be summarized as follows:

- Instruments made of the titanium-aluminium alloy showed nearly the same cutting efficiency as corresponding conventional stainless steel instruments. K-files made of the nickel-titanium alloy showed the poorest cutting efficiency of all instruments tested (Fig. 3a).
- All stainless steel instruments had a greater cutting efficiency than nickel-titanium instruments. With few exceptions, stainless steel K-files displayed a greater cutting efficiency than stainless steel reamers of the same brand.
- The flexible stainless steel instruments showed the greatest cutting efficiency, and were significantly superior to all other instruments (Fig. 3b).
- In the group of flexible stainless steel instruments, the K-Flexofiles and the K-Flexoreamers showed the greatest cutting efficiency (Fig. 4).

Linear working motion

Cutting efficiency in a linear, filing motion was determined by a specially designed test apparatus, which has been described in detail previously (9). The specimens were made of polyester resin (Alpolit UP 004, Hoechst) to which 5% wt quartz powder was added. The specimen thickness was 1 mm. The instrument to be tested was fixed in the apparatus and placed on the specimen, and every test run was continued until the instrument was blunt, i.e., until the instrument no longer removed any material, thereby creating maximum groove depth. The depth of the groove was used as the measure of cutting efficiency (10).

With regard to cutting efficiency in a linear motion, the Hedström files removed far more material than K-files or reamers (Fig. 5) (10) confirming the results of previous studies (11, 12).

However, Hedström files made by different manufacturers showed significant differences in their cutting efficiency (Fig. 6) (10).

Modifications of the traditional Hedström file are the S- and U-files which have a double-helix design.

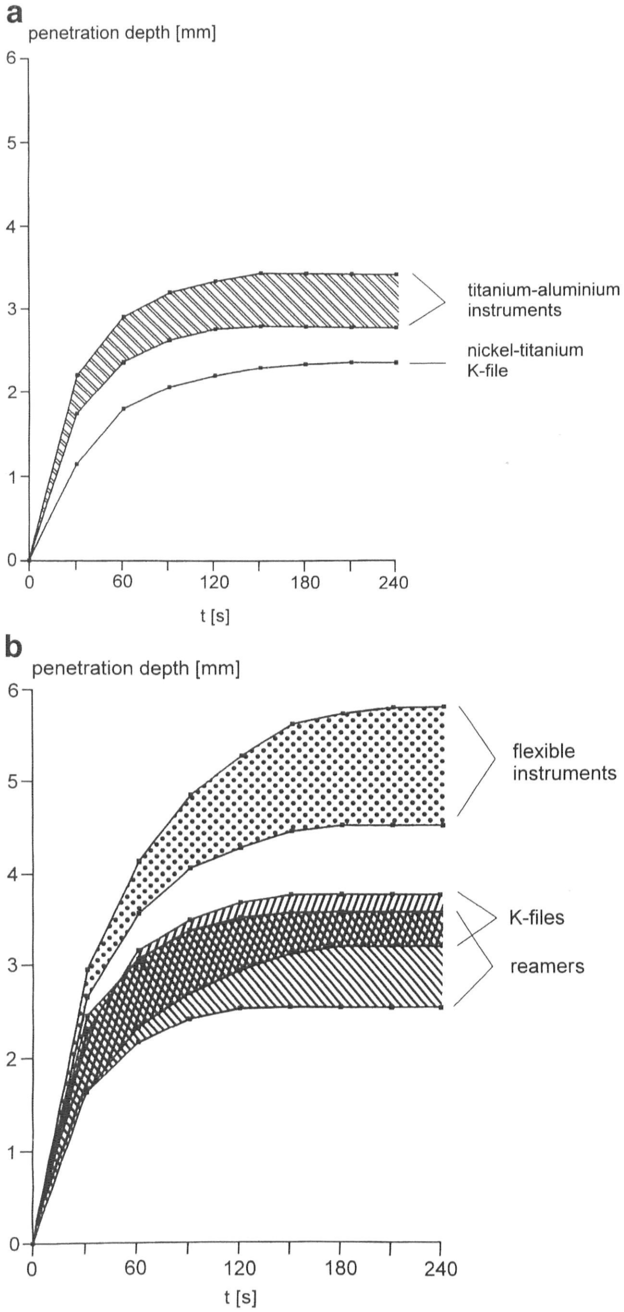

Fig. 3. Overview of the cutting efficiency of root canal instruments used in a rotary motion (ISO size 25). The maximum penetration depth which was reached at the end of each experiment served as the measure for cutting efficiency. All instruments in each group showed maximum penetration depths within the hatched area. a) Titanium based instruments. b) Stainless steel instruments. The group of flexible stainless steel instruments reached a significantly greater maximum penetration depth than all other instruments.

Compared with most Hedström files, these instruments displayed significantly lower cutting efficiency (9). Hedström files made of stainless steel displayed greater cutting efficiency than files made of nickel-titanium or titanium-aluminium alloys.

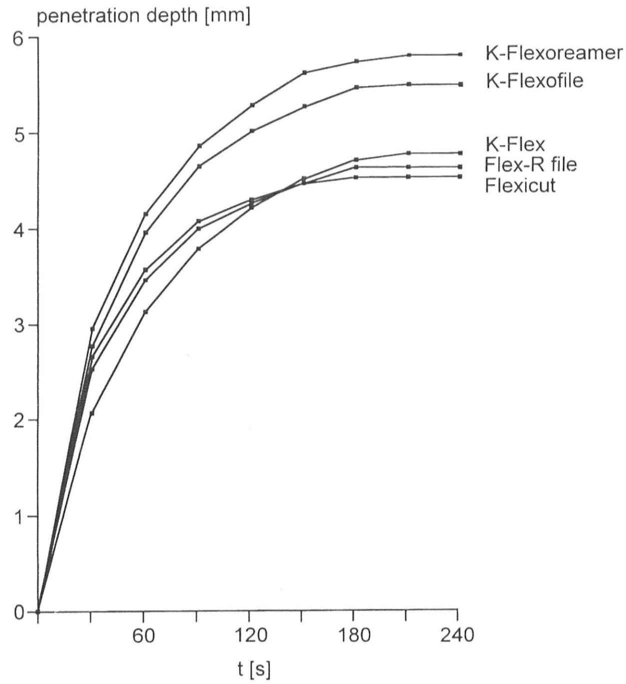

Fig. 4. Cutting efficiency of flexible stainless steel instruments used in a rotary motion in detail (ISO size 25, mean, $n=12$).

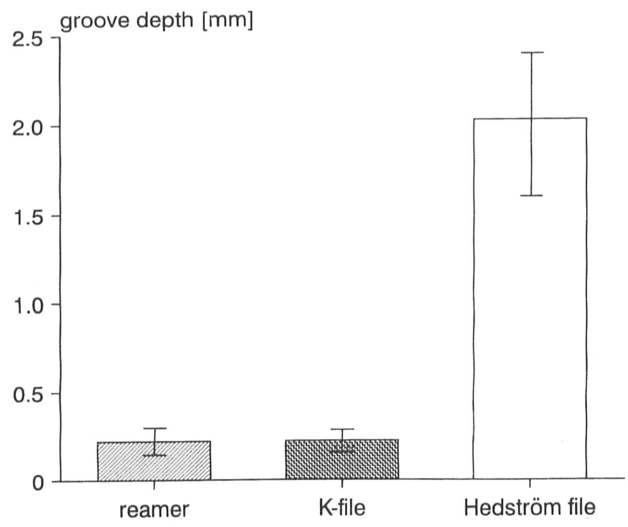

Fig. 5. Maximum groove depth (mean, SD, $n=12$) of new root canal instruments (ISO size 25, VDW, Munich, Germany) used in a linear, filing motion. In this working motion Hedström files remove far more material than reamers or K-files.

Instrumentation of curved canals

Undesirable shapes of instrumented curved canals may jeopardize bacteria-tight filling of the canals. This is especially the case when the smallest diameter of the enlarged canal is not located at the apical constriction but more coronally. Undesirable shaping effects, such as ledging, zip and elbow configurations

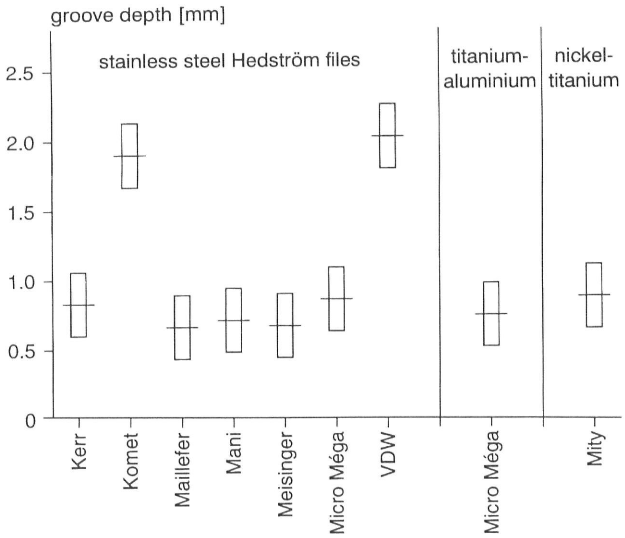

Fig. 6. Maximum groove depths of new Hedström files used in a linear, filing motion (ISO size 25). The horizontal line shows the mean of each test group (n=12), the bar represents the result of the statistical analysis (ANOVA, Scheffé, α=0.05). The difference between two groups is significant if the bars of the groups do not overlap.

and straightening, are reported to occur frequently in curved canals (13). It would be desirable, therefore, to have root canal instruments which would allow adequate centrical enlargement of curved canals, if possible without manipulating the instruments by precurving or removing the flutes on one side of the precurved instrument (13).

Certainly, Hedström files used in a linear working motion take off a maximum of root canal dentin in a minimum of time, but using them in a filing motion down to the working length resulted in a straightening of the inner canal wall as well as excessive material removal from the outer side of the curvature (11, 14, 15). Hence, instrumentation of the apical part of curved canals using Hedström files seems not to be recommendable.

The investigations on the instrumentation of curved canals were performed under standardized conditions, using selfmade specimens of clear polyester resin (Alpolit UP 004, Hoechst) with simulated colored root canals. The simulated canals, with diameter and conicity equivalent to ISO size 15, were 14 mm long, the straight part being 6.5 mm and the curved part 7.5 mm. The curvature was mathematically defined with a radius of 5.5 mm and an angle of 42° in accordance with the method described by Schneider (16). Changes in canal shape were measured and quantified at ×40 magnification at seven measuring points at 1 mm intervals beginning at the apical end of the canals. The canals were enlarged size by size from ISO size 15 to ISO size 35. The instrumentation was carried out using the same testing device as for the investigations on cutting efficiency in a rotary motion on straight canals. A 110° clockwise rotary motion was used.

Different root canal instruments

All instruments caused undesirable instrumentation effects in the curved canals (17, 18). None of the instruments used gave a centrical enlargement in terms of equal material removal from the inner and outer side of the curvature. In fact, no instrument removed material from the whole length of the inner side of the curvature. On the other hand, all instruments removed material from the outer side of the curvature. The resulting canal shape depended on the type of instrument used (Fig. 7).

- Conventional stainless steel reamers and K-files caused severe bulging of the outer side of the curvature, whereas on the inner side, no material was removed from the 3.5 mm of the canal wall closest to the apex. Coronal to this uninstrumented part, the inner curves of the canals were clearly straightened.
- Reamers and K-files made of titanium-aluminium alloy created nearly the same undesirable shaping effects as the corresponding stainless steel instruments.
- Instrumentation with nickel-titanium K-files did not have any undesirable shaping effects, but they did not remove material from the inner side along the 3.5 mm closest to the apex.
- Flexible stainless steel instruments with conven-

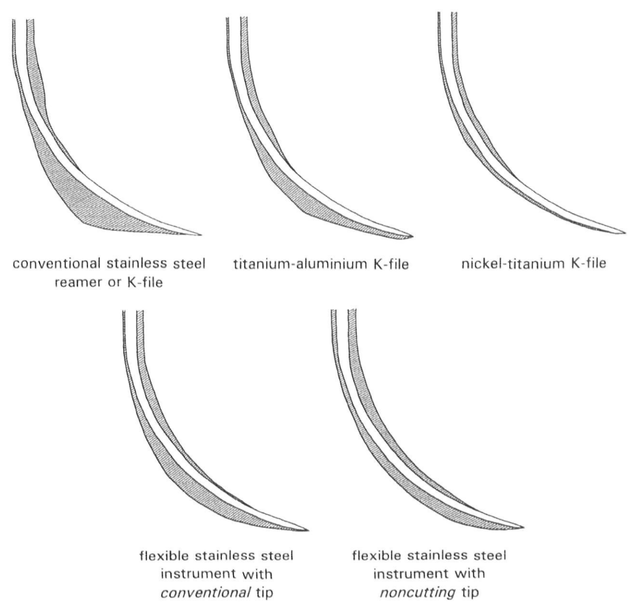

Fig. 7. Mean changes in the canal shape (angle corresponding to Schneider's method (16): 42°, radius: 5.5 mm, n=12) as a result of instrumentation with different root canal instruments used in a rotary, reaming motion (110° clockwise rotation).

Table 2. The different instrumentation techniques tested. Each working cycle generated by the computer-driven testing device consisted of three consecutive phases. First, the instrument was inserted into the canal; second, the instrument was rotated; and third, the instrument was removed from the canal. The differences between the instrumentation techniques mainly concerned the rotation of the root canal instrument

Instrumentation technique	Rotation
Reaming motion	110° clockwise rotation
Wildey & Senia (21)	90° clockwise rotation followed by 90° counterclockwise rotation
"Balanced force" technique (19)	180° clockwise rotation followed by 180° counterclockwise rotation
"Step-back" technique (22)	110° clockwise rotation. From ISO size 25 on, each instrument was inserted 1 mm shorter into the canal than the preceding one
"Combined technique" (23)	ISO sizes 15 and 20: reaming motion ISO sizes 25 to 35: "balanced force" technique

tional tips created a moderate straightening of the inner side of the curvature. On average, no material was removed from the inner side of the last 1.5 mm from the apical end.

- Flexible stainless steel instruments with modified tips (K-Flexofile Batt-tip, K-Flexoreamer Batt-tip and Flex-R file) removed material nearly equally well from the inner and outer side of the curvature, except at the 1.0 mm of the inner side nearest the apex where no material was removed. Straightening of the canal was very slight.

The results showed that flexible stainless steel instruments are a substantial improvement compared with conventional stainless steel reamers and K-files and, somewhat surprisingly, that they perform better in curved canals than the flexible titanium-based instruments tested. Moreover, the results pointed out the great importance of the instruments' tip design as the instruments with noncutting tips were clearly superior to those with conventional tips.

The influence of tip design on canal shape could also be shown by comparing the effect of flexible stainless steel instruments with conventional tips and the same instruments with noncutting tips (5). The instruments with noncutting tips maintained the original canal curvature far better than the instruments with conventional tips, apparently owing to a better centrical guidance in the curved canal, and thus resulting in almost centrical enlargement (19, 20).

Different instrumentation techniques

As appears from the above, flexible stainless steel instruments with noncutting tips used in a rotary motion perform better in curved canals than other instruments. The question then arises of whether the instrumentation technique itself can influence the shape of a curved canal when these instruments are used. The reaming motion and the techniques described by Wildey & Senia (21), the "balanced force" technique (19), the "step-back" technique (22) and a previously described combination of the reaming motion and the "balanced force" technique (23) were tested.

All these techniques had an element of rotary working motion.

Independent of the technique, the root canal instrument was first introduced into the canal until it came in contact with the canal wall. Then a rotary movement, which depended on the specific technique, followed, and finally the instrument was removed from the canal (Table 2). The experiments were done using the simulated curved canals described above. The canals were enlarged with flexible stainless steel instruments with noncutting tips size by size from ISO size 15 to ISO size 35 using the computer-driven testing device, which generated the particular working motion. These were our findings (Fig. 8) (23):

- Curved canals shaped with a simple reaming working motion (110° clockwise rotation) showed only a slight straightening. On the inner side of the curvature no material was removed from the 1 mm of the canal nearest the apex.
- Using the technique introduced by Wildey & Senia (90° clockwise rotation followed by a 90° counterclockwise rotation) (21), the canal showed only a slight straightening. No material was removed from the inner side of the curvature at the 3.5 mm of the canal nearest the apex.

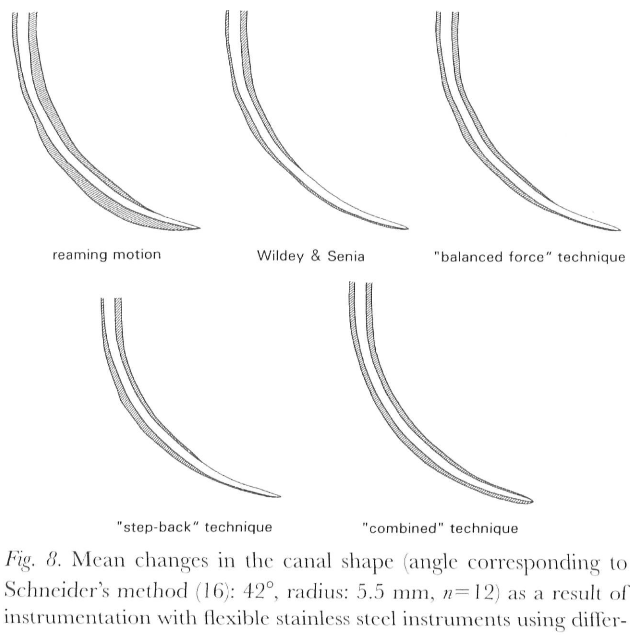

Fig. 8. Mean changes in the canal shape (angle corresponding to Schneider's method (16): 42°, radius: 5.5 mm, $n=12$) as a result of instrumentation with flexible stainless steel instruments using different instrumentation techniques.

Fig. 9. Bending moments of the investigated root canal instruments (ISO size 25, mean, SD, $n=10$). The greater the bending moment of an instrument, the more it will straighten inside a curved canal. The maximum bending moments which, according to ISO standard 3630-1 (3) the instruments should not exceed, are indicated by the horizontal lines.

- Instrumentation using the "balanced force" technique (180° clockwise rotation followed by a 180° counterclockwise rotation) (19) resulted in only a slight straightening of the curved canal. No material was removed from the inner side of the curvature at the 2 mm closest to the apex.
- Canals enlarged by the "step-back" technique (110° clockwise rotation, each instrument from size 25 was withdrawn 1 mm short of the preceding instrument) (22) showed moderate bulging of the outer side of the curved canal. No material was removed from the inner side of the curvature at the 2.5 mm of the canal closest to the apex.
- The most appropriate canal shape resulted from a combination of a reaming motion (110° clockwise rotation) with size 15 and 20 instruments followed by the "balanced force" technique (180° clockwise rotation followed by a 180° counterclockwise rotation) with the subsequent instrument sizes up to size 35 (23). The canals were not straightened and material was removed from the inner curve of the canal except in some instances in the 1 mm closest to the apex.

In accordance with our results, several authors have reported better instrumentation of curved canals with the "balanced force" technique as compared to the "step-back" technique (24, 25).

Bending properties

In the ISO standard 3630-1 (3), several mechanical requirements for root canal instruments are listed. One of these requirements concerns the resistance to bending. In order to determine the resistance to bending of a root canal instrument, the instrument is fixed at its tip over 3 mm and bent. The bending moment at a bending angle of 45° is determined.

The experiments on the resistance to bending of the instruments of this study gave the following results (Fig. 9) (26):

- In the group of stainless steel instruments, the flexible stainless steel instruments displayed 20–40% less resistance to bending than conventional stainless steel reamers and K-files of the same brand, which showed the greatest resistance to bending of all instruments tested. Stainless steel reamers and

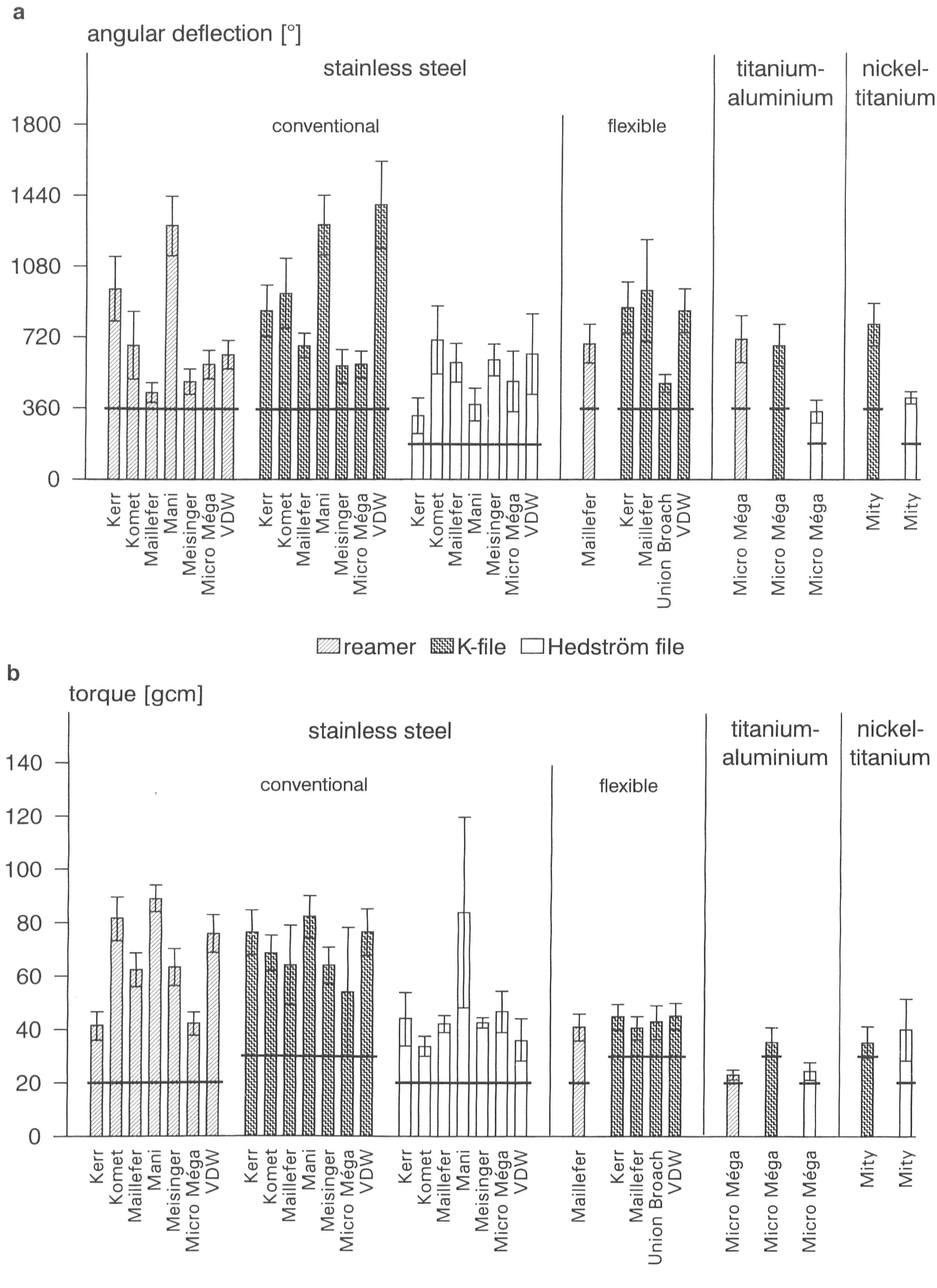

Fig. 10. a) Angular deflection and b) torque of the investigated root canal instruments (ISO size 25, mean, SD, $n=10$). In tests according to ISO standard 3630-1 (3) the instrument was fixed at its tip and rotated clockwise until it fractured. The minimum requirements given by ISO standard 3630-1 (3) are indicated by the horizontal lines.

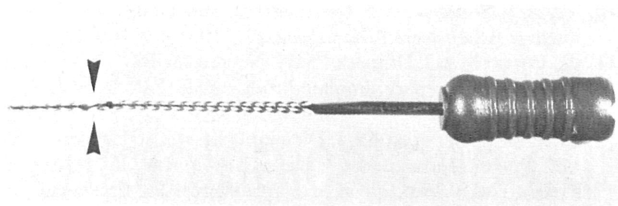

Fig. 11. Unwound K-file (rotation angle: 360°). Instruments showing nonelastic deformation should be discarded.

K-files displayed a greater resistance to bending than stainless steel Hedström files. There were no consistent differences between conventional stainless steel reamers and K-files.

- Instruments made of a titanium-aluminium alloy displayed a lower resistance to bending than both corresponding conventional and flexible stainless steel instruments, but a greater resistance to bending than nickel-titanium instruments.
- Nickel-titanium instruments showed far less resistance to bending than all other instruments. For example, these instruments displayed 50–75% less resistance to bending than corresponding conventional stainless steel instruments.

Similar results have been reported in previous studies (27–30).

The question then arises of whether the low resistance to bending of the nickel-titanium instruments makes them superior in the preparation of curved canals. The results of our studies do not necessarily show that. Certainly, nickel-titanium K-files caused few undesirable changes in the shape of curved canals, but this was mainly because almost no material was removed from the canal walls because of the rapid wear of these instruments. Clearly, the flexible stainless steel instruments which showed a greater resistance to bending than the nickel-titanium instruments performed better in curved canals. Thus, it may appear that resistance to bending is not necessarily a good criterion for the clinical selection of root canal instruments.

Torsional properties

Investigations on resistance of root canal instruments to fracture have been performed for more than 50 years (31) and are part of the ISO standard 3630-1 (3).

In these tests the root canal instrument is fixed at its tip and at its shaft and then rotated in a clockwise direction until it fractures. During the tests, the rotation angle and torque are continuously recorded in order to calculate the angular deflection, i.e., the torsional angle at which the instrument fractures, and the torque from these records. The angular deflection is meant to give information about the risk of torsional fracture if an instrument binds at its tip in the root canal and is rotated further. The torque has a clinical impact with respect to nonelastic deformation since instruments with low torque values tend to unwind at lower forces than those with high torque values.

Experiments on the resistance to fracture of the instruments in this study gave the following results (Fig. 10) (26):

- In the group of conventional stainless steel instruments, the Hedström files on average fractured after one to two revolutions. A few Hedström files even fractured after about half a revolution. The average angular deflection of conventional reamers and K-files was greater than that of Hedström files, and they fractured after two to three revolutions. Nevertheless, in isolated cases, reamers and K-files fractured after a little more than one single revolution. K-files mostly reached greater angular deflection than reamers of the same brand. Most Hedström files showed lower values than reamers and K-files of the same brand.
- The average angular deflection of flexible stainless steel instruments was similar to that of conventional reamers and K-files. The flexible stainless steel instruments displayed less torque than the conventional stainless steel instruments.
- Instruments made of titanium-aluminium alloys (Hedström files, reamers and K-files) reached about the same angular deflection as corresponding stainless steel instruments. Their average torque was less than with the corresponding stainless steel instruments.
- Nickel-titanium instruments (Hedström files, K-files) reached about the same angular deflection as corresponding stainless steel instruments. Their average torque was less than with the corresponding stainless steel instruments.

The following clinical implications may be drawn from these results:

- Commonly used instrumentation techniques require rotation angles between 90° and 180° for the rotary movement of an instrument in the root canal (19, 21, 23). Even if the instrument binds at its tip at the beginning of this rotation, twisted instruments (reamers and K-files) will not break because the rotation angle where the instrument fracture is likely to occur is much greater than 180°. Nevertheless, they will undergo nonelastic deformation. Twisted stainless steel instruments will show an obvious unwinding which is a warning signal that the instrument should be discarded (Fig. 11). Milled instruments, such as Hedström files, do not give this warning signal since they are machined into a round blank. They should therefore not be used with rotary working motions (26, 32–34).
- The observed differences in torque values of the various instruments will be clinically visible since instruments with low torque values will unwind

more easily than those with high torque values. However, the low torque instruments can be used without any increased risk of instrument fracture if they are checked during instrumentation for non-elastic deformation and discarded as soon as an unwinding of the flutes has occurred.

- All instruments tested fulfilled the minimum requirements of the ISO standard 3630-1 (3). This is important, but in our opinion, the most important parameters for evaluating root canal instruments from a clinical point of view are cutting efficiency and behavior during the instrumentation of curved canals. These two parameters should serve as useful complements to existing international standards.

Conclusions

- With regard to cutting efficiency in a rotary motion, flexible stainless steel instruments are superior to conventional stainless steel reamers and K-files as well as nickel-titanium instruments.
- With regard to cutting efficiency in a linear motion, stainless steel Hedström files display the best results.
- Concerning the instrumentation of curved canals, flexible stainless steel instruments with noncutting tips cause far less transportation of the canal than other instruments, even instruments made of titanium-based alloys.
- The risk of torsional fracture of flexible stainless steel reamers and K-files is no higher than that of conventional stainless steel reamers and K-files.

References

1. Schäfer E. Root canal instruments for manual use: a review. *Endod Dent Traumatol* 1997; *13:* 51–64.
2. Civjan S, Huget EF, De Simon LB. Potential application of certain Nickel-Titanium (Nitinol) alloys. *J Dent Res* 1975; *54:* 89–96.
3. International Organization for Standardization: ISO 3630-1. Dental root-canal instruments – part 1: files, reamers, barbed broaches, rasps, paste carriers, explorers and cotton broaches. Geneva: ISO 1992.
4. Schäfer E, Tepel J, Hoppe W. Die Schneidleistung von Wurzelkanalinstrumenten bei drehend-schabender Arbeitsweise. *Dtsch Zahnärztl Z* 1992; *47:* 781–5.
5. Tepel J, Schäfer E, Hoppe W. Root canal instruments for manual use: cutting efficiency and instrumentation of curved canals. *Int Endod J* 1995; *28:* 68–76.
6. Tepel J, Schäfer E, Hoppe W. Kunststoffe als Modellmaterial in der Endodontie. *Dtsch Zahnärztl Z* 1993; *48:* 736–8.
7. Hoppe W, Heinsen JP. Schärfe-Grenzwerte von Wurzelkanalbohrern und Hedströmfeilen und ihre Bedeutung für die Wurzelkanalaufbereitung. *Dtsch Zahnärztl Z* 1983; *38:* 209–13.
8. Tepel J, Schäfer E, Hoppe W. Properties of endodontic hand instruments used in rotary motion. Part 1. Cutting efficiency. *J Endod* 1995; *21:* 418–21.
9. Schäfer E, Tepel J. Cutting efficiency of Hedström, S and U files made of various alloys in filing motion. *Int Endod J* 1996; *29:* 302–8.
10. Tepel J, Schäfer E. Schneidleistung von Hedströmfeilen bei linearer Arbeitsweise. *Dtsch Zahnärztl Z* 1995; *50:* 109–11.
11. Al-Omari MAO, Dummer PMH, Newcombe RG. Comparison of six files to prepare simulated root canals. Part 1. *Int Endod J* 1992; *25:* 57–66.
12. Platzer U, Sedelmayer J. Die manuelle Wurzelkanalaufbereitung: Neue Instrumente – neue Techniken? In: Akademie Praxis und Wissenschaft, ed. *Endodontie: Neue Erkenntnisse aus Praxis und Wissenschaft.* Munich: Hanser, 1993.
13. Weine FS. *Endodontic therapy.* 4th ed. St. Louis: Mosby, 1989.
14. Al-Omari MAO, Dummer PMH, Newcombe RG. Comparison of six files to prepare simulated root canals. Part 2. *Int Endod J* 1992; *25:* 67–75.
15. Hoppe W, Schäfer E, Tepel J. Instrumentarium und Konzept für die manuelle Wurzelkanalaufbereitung. *Zahnärztl Welt* 1993; *102:* 764–71.
16. Schneider SW. A comparison of canal preparations in straight and curved canals. *Oral Surg Oral Med Oral Pathol* 1971; *32:* 271–5.
17. Schäfer E, Tepel J, Hoppe W. Vergleichende Untersuchung von Wurzelkanalinstrumenten aus herkömmlichem Stahl und Nickel-Titan-Legierungen. *Endodontie* 1994; *3:* 185–97.
18. Schäfer E, Tepel J. Formveränderungen gekrümmter Wurzelkanäle nach standardisierter Aufbereitung. *Dtsch Zahnärztl Z* 1993; *48:* 653–8.
19. Roane JB, Sabala CL, Duncanson MG. The "balanced force" concept for instrumentation of curved canals. *J Endod* 1985; *11:* 203–11.
20. Sabala CL, Roane JB, Southard LZ. Instrumentation of curved canals using a modified tipped instrument: a comparison study. *J Endod* 1988; *14:* 59–64.
21. Wildey WL, Senia EE. A new root canal instrument and instrumentation technique. *Oral Surg Oral Med Oral Pathol* 1989; *67:* 198–207.
22. Clem WH. Endodontics: the adolescent patient. *Dent Clin North Am* 1969; *13:* 483–93.
23. Schäfer E. Effects of four instrumentation techniques on curved canals: a comparison study. *J Endod* 1996; *22:* 685–9.
24. Backman CA, Oswald RJ, Pitts DL. A radiographic comparison of two root canal instrumentation techniques. *J Endod* 1992; *18:* 19–24.
25. Baumgartner JC, Martin H, Sabala CL, Strittmatter EJ, Wildey WL, Quigley NC. Histomorphometric comparison of canals prepared by four techniques. *J Endod* 1992; *18:* 530–4.
26. Tepel J, Schäfer E, Hoppe W. Properties of endodontic hand instruments used in rotary motion. Part 3. Resistance to bending and fracture. *J Endod* 1997; *23:* 141–5.
27. Dolan DW, Craig RG. Bending and torsion of endodontic files with rhombus cross-section. *J Endod* 1982; *8:* 260–4.
28. Krupp JD, Brantley WA, Gerstein H. An investigation of the torsional and bending properties of seven brands of endodontic files. *J Endod* 1984; *10:* 372–80.
29. Städler P, Jeglitsch M. Elastizität und Maßtreue endodontischer Aufbereitungsinstrumente. *Endodontie* 1993; *2:* 25–31.
30. Walia H, Brantley WA, Gerstein H. An initial investigation of the bending and torsional properties of Nitinol root canal files. *J Endod* 1988; *14:* 346–51.
31. Schultz H. Der Einfluß der Heißluftsterilisation auf die Torsionsfestigkeit der Wurzelkanalinstrumente. *Schweiz Monatsschr Zahnheilk* 1944; *54:* 239–65.
32. Haikel Y, Gasser P, Allemann C. Dynamic fracture of hybrid endodontic hand instruments compared with traditional files. *J Endod* 1991; *17:* 217–20.
33. Olschner D. Experimentelle Untersuchungen über die Materialeigenschaften des derzeitigen Feininstrumentariums zur Wurzelkanalbehandlung. [Medizinische Dissertation]. University of Bonn, 1977.
34. Tronstad L. *Clinical endodontics.* Stuttgart: Thieme, 1991.